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EVIDENCE FOR A $16^{\mathrm{d}}.6$ PERIOD FROM CIRCINUS X-1

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ABSTRACT

Analysis of All-Sky Monitor observations of Cir X-1 (3U1516-56) over the period October 1975 - April 1976 has revealed a well-defined modulation of the 3-6 keV flux at a period of $16^{\mathrm{d}}.585 \pm 0^{\mathrm{d}}.01$. The light-curve is characterized by an abrupt drop in emission occurring on a timescale of $\leq 0^{\mathrm{d}}.07$, with epoch JD 2,442,877.181 $\pm$ $0^{\mathrm{d}}.07$. No clear correspondingly sharp increase in emission is observed during the cycle, so that a non-eclipse origin for this effect cannot be ruled out.

Subject Headings: X-rays: sources -- stars: binaries

I. INTRODUCTION

Circinus X-1 (3U1516-56) has been studied in X-rays with observations dating back to at least 1969 (Margon et al. 1971) and probably earlier (Harries et al. 1971). Particular interest in the source has resulted from the resemblance of its short-timescale variability to that of Cyg X-1 (Spada et al. 1974) and an eclipse-like behavior reported by several observers (Tuohy and Davison 1973; Jones et al. 1974), for which

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no period consistent with all observations has been found. This study has been complicated by the long-term variability of Cir X-1 (i.e. "extended lows" similar to those of Cen X-3), and the relatively short observing time possible with most instruments prior to the launch of Ariel 5. We report in this Letter some observations of Cir X-1 by the All-Sky Monitor (ASM) which reveal a well-defined modulation at a period of $16\overset{d}{.}585 \pm 0\overset{d}{.}01$.

II. EXPERIMENTAL RESULTS

The ASM consists of a pair of 1 cm^2 pinhole camera detectors which provide virtually continuous coverage of $> 80\%$ of the X-ray sky in the 3-6 keV energy band. A complete description of the experiment can be found in Holt (1976). Temporal resolution is defined by the time for one orbit (~ 1.7 hours), and the inherently low counting rates frequently make accumulation of the single-orbit data into $\sim 1/2$ day integrations useful in improving the experimental sensitivity. Two operational modes are possible, a coarse (spatial) resolution mode with typical positional accuracy of $\sim 5^{\circ}$ and a "fine" mode with a factor of ~ 4 times finer resolution. This latter mode is especially useful when source confusion or relatively high background conditions exist, but its use must be confined to only 1/16 of the sky (i.e. at the expense of all-sky coverage).

From the launch of the Ariel 5 in mid-October 1974 thru August 1975, Circinus X-1 was not unambiguously detected above the coarse-mode ASM threshold ($\simeq 0.1$ cm^{-2}-sec^{-1}), and observations conducted by the Sky Survey Experiment on Ariel 5 in November 1974 and again in March 1975 failed to detect the source above a level of ~ 0.01 cm^{-2}-sec^{-1} in the

1.2-19.8 keV range (Kaluzienski et al. 1975). In October 1975 Cir X-1 exhibited a significant increase ($\gtrsim$ factor of 10) in the 3-6 keV flux, signalling the commencement of a new phase of heightened activity. The source subsequently fluctuated between approximately 0.05 and 1.5 cm^{-2}-sec^{-1} thru February 1976, after which the peak intensity gradually declined to ≤ 0.1 cm^{-2}-sec^{-1} by late April 1976. As shown in Figure 1, order-of-magnitude variations over timescales ≤ 1 day are not uncommon, and the light-curve bears little resemblance to that of any known occulting X-ray binary.

Periodic modulation of the flux was searched for by folding the data over trial periods between ~ 14-20 days, the range below $14^{d}.3$ having been effectively ruled out by Uhuru (Jones et al. 1974) and OSO-7 (Canizares et al. 1974) observations. A significant peak in the χ^2 vs. period distribution (against the hypothesis of a constant source intensity) occurred near $16^{d}.55$, with a corresponding light curve characterized by a relatively short (≤ 4 days) interval of high-level emission followed by an abrupt fall-off to minimal flux. To improve the precision of our determination of the period, transition epoch, and duration of a possible occultation, the single-orbit data were inspected and revealed six clear instances in which the Cir X-1 count rate dropped from relatively high to low levels on adjacent orbits. Two such transitions are illustrated in Figure 2, where the sharpness of the decrease in flux is apparent, occurring over a timescale of $\leq$ one orbit ($\simeq 0^{d}.07$). Taking the end-time of the last "on" orbit for the time of transition and an accuracy of $\pm$ one orbit, a least-squares fit to a constant period yielded

$P = 16\overset{d}{.}585 \pm 0\overset{d}{.}01$, and transition epoch JD 2,442,877.181 $\pm$ $0\overset{d}{.}07$, where the quoted errors are $\sim 3/2$ the square root of the respective fit variances. Since the effective ASM single-orbit (coarse-mode) sensitivity is $\simeq 0.2$ cm^{-2}-sec^{-1} in a region as confused as Circinus, the points following the transition in Figure 2 are not definitive. A fine-mode observation of a transition on 8 April 1976 showed a possible detection at ~ 0.05 cm^{-2} sec^{-1} as early as 4 orbits ($0\overset{d}{.}33$) later, but was followed by another 6 orbits ($0\overset{d}{.}42$) in which no detectable signal at this level was observed. A more sensitive instrument is clearly required to determine the eclipse duration, if this is indeed the origin of the present effect.

Figure 3 shows all the data of Figure 1 folded modulo $16\overset{d}{.}585$, with phase 0.0 centered on the epoch of rapid transition from high to low intensity. The asymmetric nature of the emission over the cycle is again quite evident, with the bulk of the source activity occurring at phase $\gtrsim 0.75$. No sharp emergence from an "eclipse" is apparent, in contrast to the *Uhuru* observation of 9-17 May 1972 (Jones *et al.* 1974) and to the behavior of the occulting X-ray binaries Cen X-3, Her X-1, and Vela X-1. We note that the scatter of points at phase $\gtrsim 0.75$ is due primarily to the folding of cycles of differing peak intensity, and not to variations within each cycle (see Figure 1).

III. DISCUSSION

We have searched the literature for observations of Circinus X-1 for comparison with the present result. Of particular relevance are the *Uhuru* observation of an eclipse-like transition in May 1972 (Jones *et al.* 1974) and a *Copernicus* observation of an "off state" in June 1973

(Tuohy and Davison 1973). The *Uhuru* extended minimum lasted approximately $1\overset{d}{.}3 \pm 0\overset{d}{.}3$ commencing on 1972 May 10.6 $\pm$ $0\overset{d}{.}2$, and the ~ 13 hour *Copernicus* 2-7 keV measurement (≤ 0.01 cm^{-2}-sec^{-1}) began 1973 June 14.91 $\pm 0\overset{d}{.}01$ (it is conceivable that this latter datum is merely a point measurement during an extended low state, as Cir X-1 was reported to be in such a low state two months later by the same observers, Davison and Tuohy 1975). The transition phases relative to the present definition are 0.84 $\pm$ 0.06 and 0.97 $\pm$ .03, respectively, with the latter being the phase at the start of the observation.

The supposition that the *Uhuru* transition is related to the $16\overset{d}{.}6$ modulation reported here yields an average period of $16\overset{d}{.}616$ over four years, which is just outside of the acceptable range of the present measurement alone (at 3 times the quoted error). This discrepancy implies an apparent average decrease in period of $5 \pm 3 \times 10^{-4}$ parts per year between May 1972-April 1976. It is difficult to reconcile this with either an actual decrease in the period resulting from mass transfer, or with apsidal motion with a constant orbital period. Thomas (1974) has pointed out that an order-of-magnitude smaller effect in the orbital period of Cen X-3 over 1971 (Schreier *et al*. 1973) would require an unreasonably large mass exchange rate ($\geq 2 \times 10^{-5} M_{\odot}$-yr^{-1}). An apparent change in period due to apsidal advance would require a mean apsidal period of $\sim 1800^{d}$, and would have been detectable over our data sample (i.e. the first and last transitions in the sample would each have differed from the best period expectation by more than one day, in contrast to the $\leq 0\overset{d}{.}07$ observed). Alternatively, a slower secular *recession* of the line of

apsides with period $\sim 8900^d$ would also have been detectable in the ASM data, and would imply an extremely high density ($\sim 10^{-7}$ g-cm^{-3}) of the circumstellar medium (Batten 1973).

Other relevant observations include Copernicus measurements (Davison and Tuohy 1975) of a high source intensity (~ 0.5 cm^{-2}-sec^{-1}) in short exposures on two occasions in April 1974 at ASM phases 0.70 ± 0.03 and 0.86 ± 0.09 (just over one cycle apart). We also note that Baity et al. (1975) reported 7-11 keV observations of Cir X-1 with OSO-7 (several of which extended over transition times predicted from the ASM ephemeris), but failed to detect any eclipse-like periodicities. As pointed out by the latter authors, several factors including contamination from nearby sources and possible aliasing due to periodicities in their observing schedule could have precluded their detection of such effects.

While the long-term behavior of Circinus X-1 is apparently similar to that of Cen X-3 and Vela X-1, the $16\overset{d}{.}585$ light curve is unique in several respects. Most of the emission is concentrated in flare-like episodes typically occurring late in the cycle, with negligible activity preceding phase ~ 0.5. A well-defined exit from a possible occultation is not observed, in contrast to the established binaries and the Uhuru 1972 observation. In addition, the "turn-on" from the extended low state (and subsequent return) does not resemble that of Cen X-3, where, due to decreasing absorption, the source emission gradually appears near inferior conjunction and then progressively widens to completely fill the non-occulted fraction of the orbit. The folded light-curve of Figure 3 bears little resemblance to the 35^d cycle of Her X-1, although a common

origin cannot be ruled out from our data. Mechanisms suggested to explain the 35^d cycle such as precession of the compact object (Brecher 1972), or of the primary star (Roberts 1974; Petterson 1975) may be capable of producing the apparent periodicity observed in the Cir X-1 transitions.

With regard to the long-term behavior of Cir X-1, Clark et al. (1975) have proposed a young runaway binary model in which the "on" state occurs near periastron of a highly elliptical, long-period orbit. Davison and Tuohy (1975) found that an interval of $\sim$ 220 days between times of high emission was consistent with the available x-ray data. This is difficult to reconcile with the observations reported here, since the absence of emission at $>$10% of maximum between October 1974 - mid-August 1975 implies an extended low state of $>$ 300 days. It thus appears that while the long-term variability of Cir X-1 can be characterized by fairly well-defined "high" and "low" states, no regular long-term pattern may exist.

FIGURE CAPTIONS

Figure 1 ASM observations of Cir X-1 over $\sim$ 200 days between September 1975 and April 1976. The points represent $\sim$ 1/2 day averages, and error bars reflect only the $\pm$ 1σ statistical uncertainty of each measurement. Blackened dots indicate observations made in the fine resolution mode, in which possible systematic errors due to spatial offsets and source confusion are minimized. Periods when the source was out of the effective field-of-fiew are marked by the shaded areas along the abscissa. Arrows indicate the transitions predicted from the period and ephemeris given in the text.

Figure 2 Single-orbit data near the expected times of transition on 11 November 1975 and 2 February 1976. The dashed lines are relative to the best period and transition epoch in the text.

Figure 3 Data of Figure 1 folded at the $16^{d}.585$ period, with phase 0.0 defined by the transition from high to low intensity. The scatter in the data at phases $\gtrsim$ 0.75 is due primarily to folding of cycles with differing peak intensities, and not to finer timescale variations within each cycle.

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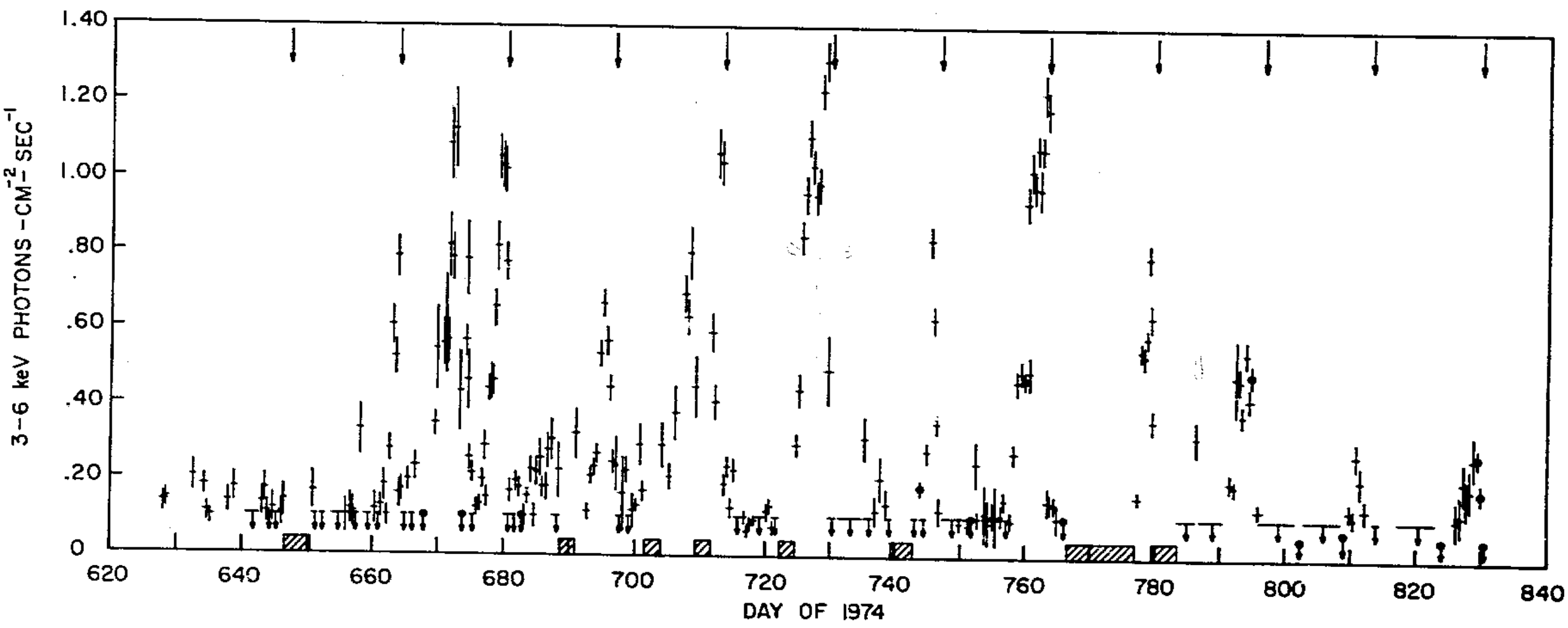

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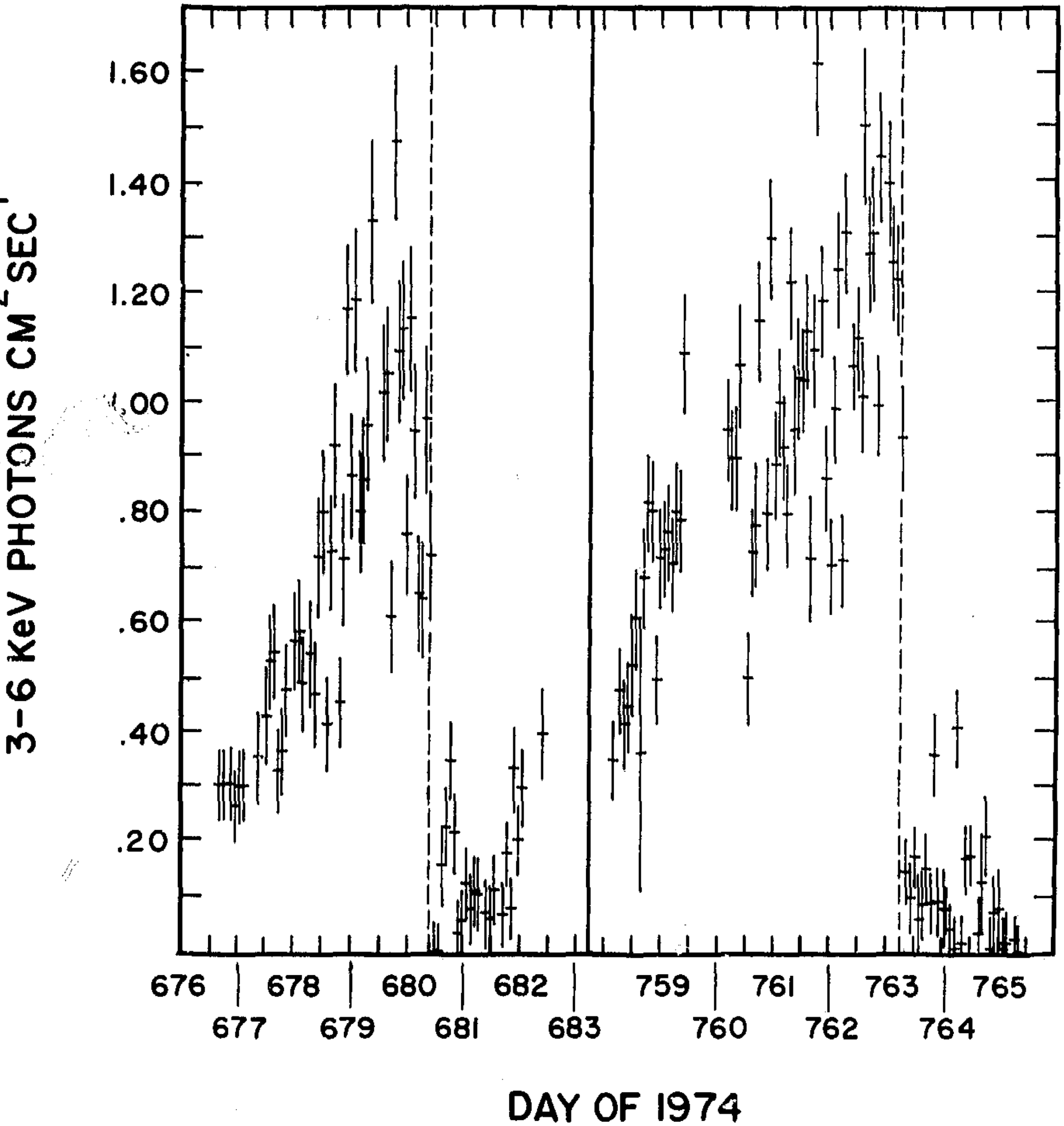
Fig. 1



3-6 KeV PHOTONS $CM^{-2}SEC^{-1}$
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Fig. 2

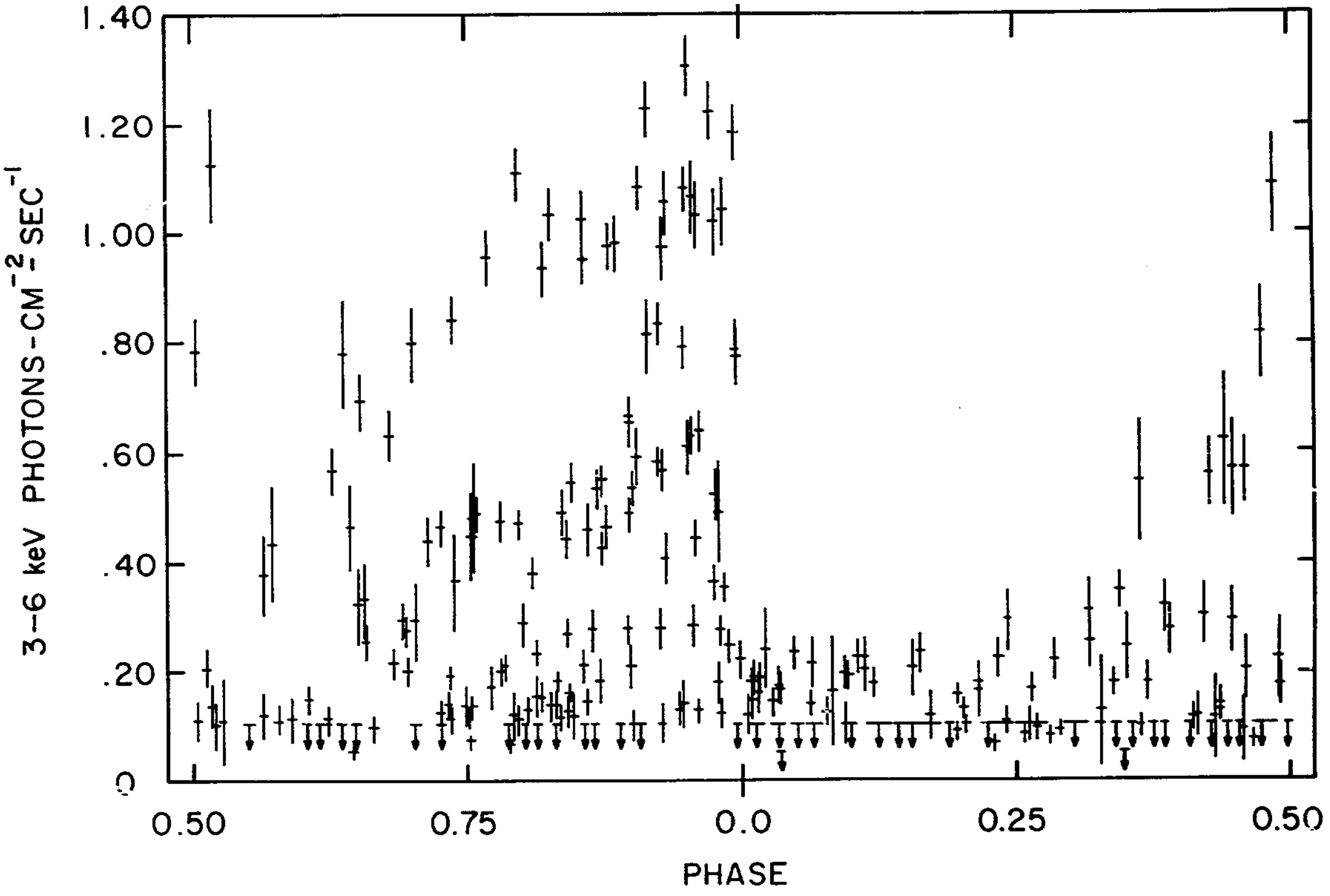
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Fig. 3